SCALLOP DREDGING: AN ENGINEERING APPROACH

P. COVER AND D. STERLING

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An appraisal of dredges used in the southeast Australian scallop fishery was undertaken and a comparison made with some scallop harvesting gear used elsewhere in the world.

Variations of the toothed mud dredge used in Australia were surveyed and described. Vertical forces on the toothed mud dredge consist of downward directed hydrodynamic lift, weight, and the upward component of the tow cable tension. These forces were analysed to show how the resultant contact pressure changed with tow speed. AMC flume tank and sea trial measurements were used to produce a mathematical model for the horizontal forces. Turning moments and dynamics during operation were analysed and modelled.

The toothed mud dredge was compared with the New Zealand dredge, Japanese Keta-ami, and Scottish mini dredge for downward contact pressures and drag forces per meter of swept width. The toothed mud dredge, keta-ami, and Scottish mini dredges exert high downward contact pressures with point loadings. The toothed mud dredge had the highest drag while the New Zealand dredge had the lowest drag especially at the lower tow speeds at which it is normally used.

P. Cover and D. Sterling, Australian Maritime College, P.O. Box 21 Beaconsfield, Tasmania 7250; 20 May, 1994.

Tasmanian, Victorian and Bass Strait scallop grounds have seen an extensive period of diminished returns and closures. The D'-Entrecastreaux Channel was closed from 1970 to 1981 and again in 1986 (Perrin,1986), and the Bass Strait Tasmanian zone was closed in 1987 (Zacharin,1991). This scallop fishery is suffering from low catch rates because of low stock levels and poor recruitment(D.P.I., Tas. Sea Fisheries data). The poor state of the fishery is partly attributed to inefficient and destructive fishing methods (McLoughlin et al,1991).

Catching efficiency of the Australian scallop 'mud' dredge was found to be low: on average only 11.6% (McLoughlin et al.,1991), and incidental damage is high for the box type dredge. High incidental damage may be detrimental to the fishery's long term viability (Zacharin,1988).

Scallop fishing gear used worldwide include box type dredges, the ring mesh bag type dredge, small multiple units and trawl gear. This gear has evolved; each in its own part of the world to suit a range of local conditions including scallop type, bottom terrain, and local technology. There is currently a drive to improve scallop harvesting gear both in efficiency (catching and engineering) and environmental impact.

To date there have been few studies of scallop dredges from an engineering viewpoint. That research includes work on: teeth and depressors (Baird,1959), drag measurements (Hughes,1973) and the pressure drop behind a stalled foil (Vaccaro & Blott,1987). Baird (1959) found that teeth improved catching efficiency and bottom contact was improved by a depressor (or diving) plate. Hughes (1973) measured typical bollard pulls and warp cable tensions for box dredges in Port Phillip Bay. Vaccaro & Blott (1987) suggested that a simple flat depressor plate at 60–75 with a gap to chord length ration of 0.27 could improve efficiency of scallop harvesting gear.

The Australian Maritime College (AMC) is cooperating with CSIRO Division of Fisheries and the Tasmanian Fisheries Department to research better scallop harvesting gear; its role is to investigate the engineering aspects of the gear.

The work conducted to date by the AMC had its objectives to: 1, survey current box dredge designs; 2, assess the engineering performance of the box dredge; 3, compare the engineering aspects of the box dredge design to designs used elsewhere in the world.

METHODS

BOX DREDGE ENGINEERING PERFORMANCE

A standard box dredge (Fig.1), as used in Australia, was constructed and analysed in flume tank and sea trials. Tests in the flume tank involved suspending the dredge in the flow by load

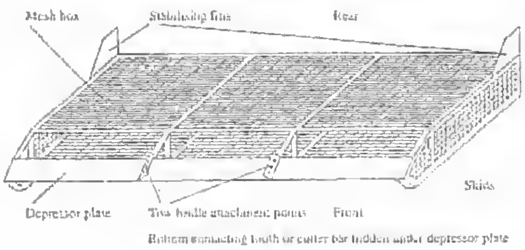

FIG.1. Schematic view of toothed mud dredge and descriptive terms

cells. This gave a measure of the downward and horizontal forces due to waterflow (hydrodynamic force). Sea trials allowed the total drag (including ground effect) to be measured and diver observations of the operational dynamics to be made. The turning moments and dynamics in operation were further analysed by mathematical modelling data from the tests. Modelling was based on equations of equilibrium applied to the system of forces acting on the box dredge.

For equilibrium or no rotation: 1, the sum of the moments about the teeth = 0 (moment arm dimensions in Fig.2). 2, the sum of the vertical forces = 0. 3, the ground reaction forces at the Front, Teeth, and Rear must always be greater than or equal to zero.

Sum of the moments = (Tow force – Hydrodynamic drag) x 0.285 – Weight x 0.413 – Upward Component of Tow Cable Tension x 0.360 + Hydrodynamic Downward Directed Lift x 0.318 – Ground Reaction at the Front x 0.200 + Ground Reaction at the Rear x 1.300

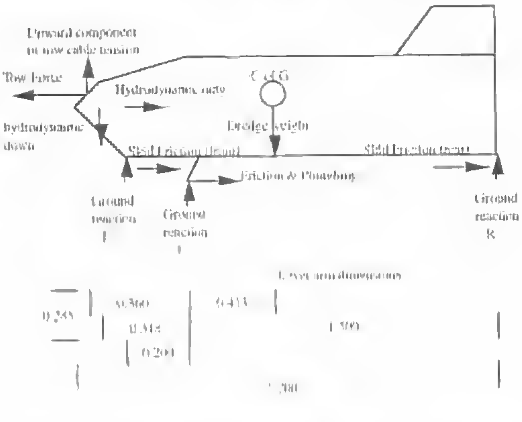

FIG.2. Diagram of forces and lever arms acting on toothed mud dredge.

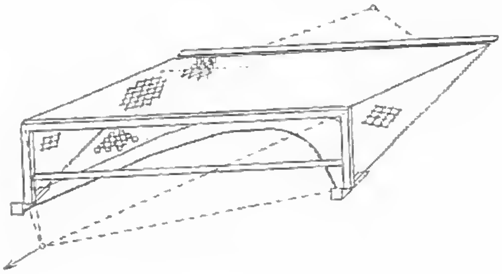

FIG.3. The New Zealand dredge.

Sum of the Vertical Forces= Weight + Hydrodynamic Downward Directed Lift – Upward Component of Tow Cable Tension – Ground Reaction at the Front – Ground Reaction at the Teeth – Ground Reaction at the Rear.

Dynamic equilibrium may exist with the ground reaction at front, teeth and rear varying dynamically in response to the terrain, sea conditions and other factors.

ENGINEERING COMPARISON OF BOX DREDGE WITH DREDGES USED ELSEWHERE

Three dredges used elsewhere in the world, obtained for comparison to the standard box dredge, were: 1, the New Zealand dredge (Fig.3) which comprises a flexible chain/ring mesh bag, tickler chain and towing frame. In New Zealand scallop fishing boats use a pair of ring bag dredges upto 2.5m wide with heavy tickler chains (Bull,1988); 2, the Japanese Keta-ami dredge (Fig.4) contains a flexible ring mesh bag with looped tickler chains mounted behind tines for use on hard mixed and rocky ground. It is designed to ride over rocky obstacles and not to

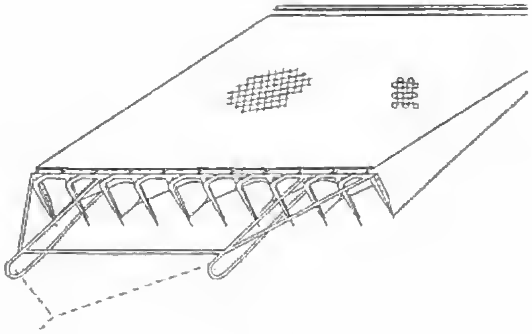

FIG.4. The Japanese Keta-ami dredge.

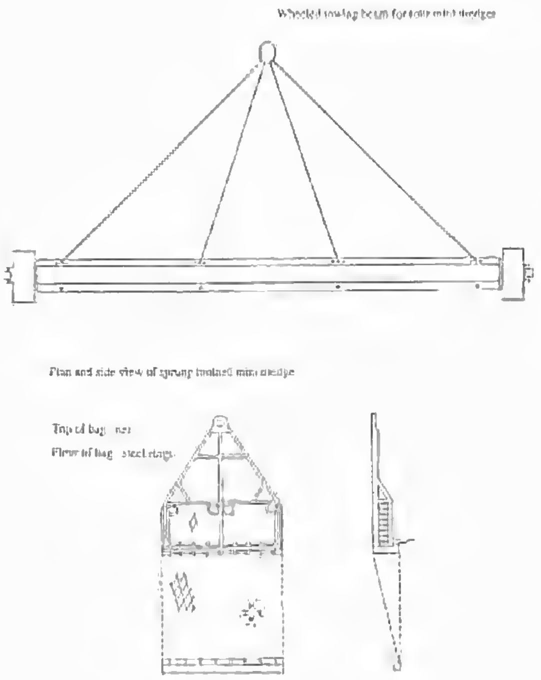

FIG.5. The Scottish mini dredges.

pick up rocks (Zacharin, pers. com.); and 3, the Scottish mini dredges (Fig.5) incorporate sprung teeth for use on hard and rocky grounds and are highly selective, not picking up rocks and other debris (Franklin, Pickett & Connor,1980). The Scottish mini dredges are normally towed in gangs of three or more from a wheeled towing beam.

The downward contact pressures applied by the dredge components were calculated from measured downward forces or weights of objects divided by their sea bed contacting area. Downward contact pressures have been compared for the dredges analysed.

Total drag of each dredge was calculated from warp tension measurements using a load cell during sea trials. The catching width for each dredge was directly measured. Total drag for the four dredge types were compared on the basis of drag per meter of swept width.

RESULTS

Survey of Box Dredge Designs

In the SE Australian scallop fishery the local fishers exclusively use a box type dredge in conjunction with a dredge tipper. This is due to the systems ease of operation and safe handling characteristics. The current dredge known as the toothed mud dredge (Gorman & Johnson,1972; Hughes,1972; Dix,1982) is a heavy (300± 150kg) steel structure composed of a steel mesh box on skids with a bottom contacting tooth bar or cutter bar and forward mounted depressor plate which also serves as the attachment point for the tow bridle.

The width of this dredge is about 3.3m but varies from 2.2–4.6m to suit boat size, width of the sorting tray and the vessel's towing capacity.

Fore to aft (length) dimensions vary only slightly between dredges irrespective of width. Typically the measurement from the back of the box to the tooth bar is about 1.2m. The box is 80–100mm above the skids. The skid length is 1.5m in a typical dredge, however forward extensions as in the Peninsula dredge modification can add up to 0.45m, while rear extensions of up to 0.3m are often used. The forward extension of the skids is a modification designed to reduce the tendency of the dredge to ride on its nose. The rearward extensions should similarly reduce the tendency for the dredge to ride on its rear.

A dredge height of 0.4m from bottom of skids to top of the box is generally adopted. Short stabilising fins are usually incorporated on each side at the rear and add an additional 0.25m to overall height.

The box type dredge generally referred to as the toothed mud dredge is often used with a device other than the tooth bar. In Port Phillip Bay it is more usual to fit a cutter bar which does not protrude below the depth of the skids. Alternatively a new device referred to as the 'mouth organ bar' can be fitted. In Bass Strait or Tasmanian waters the tooth bar normally has teeth protruding 20–60mm below the skids. The teeth are made from a hardened steel with the tips treated with hard face welding.

A variant of the box dredge known as the Bay dredge, has a long history of use in Port Phillip Bay. This dredge has the depressor plate set well forward of the box and low to the ground. The dredge is normally towed at a 5–8 knots. In one of the dredges observed, the cutter bar was angled aft in manner which would not function at all in digging up scallops from the sea bed. Intuitively the Bay dredge relies on the hydrodynamic action of the depressor to catch scallops.

On several dredges an old rubber tyre and length of chain are towed from the top rear of the box. This addition may hold the back of the dredge in ground contact or serve some dynamic purpose on rough or undulating terrain.

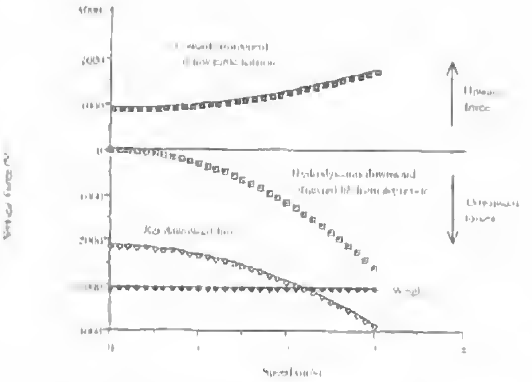

FIG.6. Vertical forces acting on toothed mud dredge modelled from lines of best fit of flume tank and sea trial data.

Dredges which have seen extensive use show high wear at the leading edges of the skids. In most cases this wear zone is patched or reinforced with hard facing weld. Dredges from Port Phillip Bay which have been extensively used exhibit thinning of the skids toward the rear. This may be due to the dredges riding harder on the rear of the skids when full or may be the result of using a short tow cable or from repeated wear during shooting away and haulback.

Box Dredge Engineering Performance

Vertical forces. Vertical forces acting on an operating dredge are: the weight, downward directed hydrodynamic lift from the depressor plate, and the upward component of the tow cable tension.

Weight of the dredge is partially reduced by buoyancy effects. The weight in water of the standard dredge was measured by suspending it in the flume tank by 'load cell' tension meters.

The hydrodynamic downward directed lift is the force exerted at right angles to the direction of flow by the deflecting action of the depressor plate. Hydrodynamic lift is generally proportional to velocity squared and was measured over a range of water speeds in the flume tank.

The upward component of the tow cable tension depends on the declination angle of the tow cable and the total drag acting on the dredge. For a completely rigorous treatment the weight and hydrodynamic drag of the tow cable should also be considered. Since the effect of cable weight and drag are relatively small they have been omitted for a more simplified view. The declination angle of the warp can be measured by an inclinometer but for the shallow depths used in the sea trials, straight line geometry can be assumed. With this assumption the declination angle can be derived from the cable length to depth ratio used. The total drag was obtained from sea trials by measuring the tow cable tension over a range of tow speeds.

The net downward force is the sum of all the vertical forces and must be greater than 0 for the dredge to stay in bottom contact.

Mathematically these three components of the vertical forces can be summed and analysed with respect to speed as follows:

–The force due to weight (W) is constant.

–The hydrodynamic force can be expressed as: $L = \rho A C_L v^2$ where v = velocity, A = area of depressor, ρ= density of water, C_L = lift coefficient of depressor.

–The upward component of the tow cable tension can be expressed as:

U = Total Dredge Drag x tan Θ Where Θ = declination angle of the tow cable or alternatively U = Total Dredge Drag x $^{1/}{}_{\text{cable length to depth ratio}}$

–The net downward force (N) is the arithmetic sum of all the vertical forces. N = W + L – U

Fig.6 shows how the vertical forces on the dredge change with speed.

Horizontal forces: The horizontal forces acting on the toothed mud dredge are the tow force (horizontal component of tow cable tension) which is equal and opposite to the drag forces. The total drag of the dredge is made up of: hydrodynamic drag, friction and ploughing forces.

The total drag was determined from sea trials

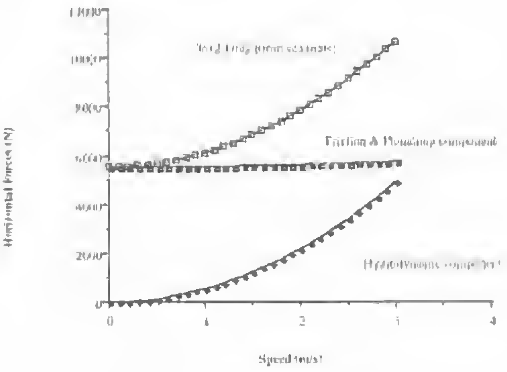

FIG.7. Horizontal forces acting on toothed mud dredge modelled from lines of best fit of flume tank and sea trial data.

TABLE 1. Estimated downward contact pressures for scallop dredges and their components. For comparison an 80kg man wearing size 8 shoes would exert a ground contact pressure of 26.1kPa.

Dredge type	Weight (in water)	Component	Contact pressure	Dynamic situation
Toothed mud	310kg (3050N)	Skids (in continuous contact) Skids (not in continuous contact) Toothed bar	12.7kPa extremely high extremely high	 point loading; fore and aft rocking
New Zealand	90kg (880N)	Skids Tickler chain Chain and ring mesh belly	18.3kPa 2.2-3.2kPa 3.9kPa	some bouncing difuse loading difuse loading
Keta-ami	270kg (2645N)	Frame Tines Tickler chain Chain and ring mesh belly	10kPa extremely high 1.2-2.0kPa 2kPa	small contact area point loading; bounces over obstacles difuse loading difuse loading
Scottish	510kg (5000N)	Wheels Teeth Chain and ring mesh belly	80kPa extremely high 7.5kPa	 point loading difuse loading

from measurements of tow cable tension over a range of tow speeds. The hydrodynamic drag component was measured in the flume tank by suspending the dredge in the flow without bottom contact. Friction and ploughing were calculated as the difference between the total drag and the hydrodynamic drag.

Hydrodynamic drag from the depressor plate and from the rest of the dredge can be expressed mathematically as:

$D = 1/2\ p\ A\ C_D\ v^2$ (i.e. proportional to velocity squared)

Friction is a mechanical force and can be considered to be independent of speed. The normal expression for friction is:

$F = \mu N$ μ = coefficient of friction:

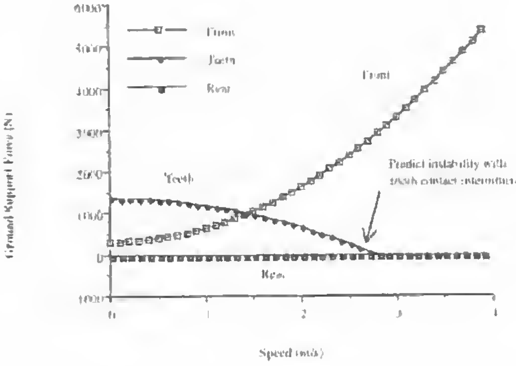

FIG.8. Ground support forces (Model 1) for toothed mud dredge at a length to depth ratio of 8 on hard ground..

N = the normal force (at right angles to the contacting surfaces).

In the case of an operational dredge the normal force is equivalent to the net downward force. Under the test conditions the net downward force increases with speed (Fig.6), therefore we would expect the friction force acting to also increase with speed.

In the ploughing force from the teeth could be a simple friction effect (i.e. independent of speed). However since the rate of ground shearing is determined by the speed of the dredge, this could lead to the ploughing force being speed sensitive.

From the trends observed in this sea trial and flume tank data with respect to speed, the horizontal force model (Fig.7) was developed.

Resultant forces and turning (rocking) moments: Configuration of all the forces acting on the toothed mud dredge (Fig.2) are such that a turning moment may exist causing the dredge to rock forward onto its nose or to rock back onto the rear of the skids. Dredge wear patterns indicate that this phenomenon commonly occurs.

The turning moments for two specific cases have been derived from the experimental data and the configuration of forces.

Modelling of all forces and resultant moments obtained by resolving ground reaction forces on skids and teeth show that where the cable length to depth ratio is greater than 7 the resultant effect suggests that the toothed mud dredge rocks forward onto its nose (Fig.8). Where a short cable length to depth ratio of 3 or less is used the dredge would ride more heavily on the rear of the skids (Fig.9).

Dynamic aspects: An observed feature of toothed mud dredge performance on hard sand bottoms is a pronounced pulsing in warp tension. This feature is affected by altering the warp length and speed and is said to have some effect on catching performance depending on the terrain. Sea trial warp tension measurements using a chart recorder have yielded pulse periods of the order of two seconds with a variation in warp tension of up to ±30%.

Approaching this phenomenon from a theoretical point of view, we can consider the dredge as having a moment of inertia (I) about a fixed point (i.e. the teeth).

We can calculate I by:

$I = \sum mr^2$ where m = mass of component, r = radius of gyration.

The forces operating are in the form of disturbing and restoring forces (or torques) (restoring torque = τ). The moment of inertia will be determined by the weight and shape of the dredge and will be constant for a particular dredge. The restoring torque will vary with the angle of the dredge (Θ) and therefore defining the restoring torque is difficult.

A natural period must exist and will depend on the restoring torque and the moment of inertia.

$T = 2\pi\,({}^{I}/\tau)^{\cdot 2}$

Engineering Comparison of Box with Other Types of Dredges

Downward contact pressures: The downward contact pressures for all four dredge types are compared in Table 1. The teeth of the toothed mud dredge and the skids if not in continuous contact will exert extremely high bottom contacting pressures. The New Zealand (Fig.3) dredge exhibits low contact pressures for all its bottom contacting elements. The Keta-ami (Fig.4) exerts extremely high bottom contact pressures at the tynes but low elsewhere. The Scottish mini dredges (Fig.5) also exert extremely high bottom contact pressures at the teeth but low elsewhere.

Comparison of drag forces per m of swept width: The toothed mud dredge has the highest drag per meter of swept width and the New Zealand dredge has the lowest drag (Fig.10).

The toothed mud dredge has the highest level of ground shear and friction type drag as well as the highest hydrodynamic drag. The ground shear and friction can be estimated by the y intercept on the drag curve (Fig.10). The hydrodynamic component is evident in the amount of increase in drag over the speed range.

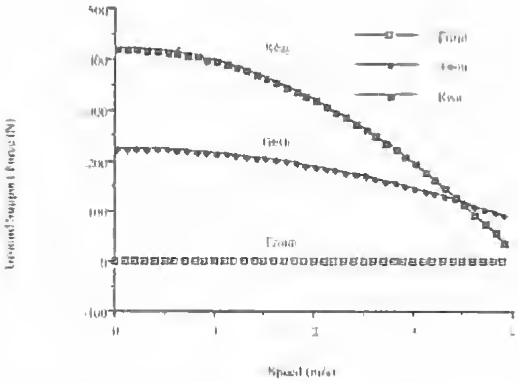

FIG.9. Ground support forces (Model 2) for toothed mud dredge at a length to depth ratio of 3 on hard ground.

The New Zealand dredge has significantly lower ground shear and friction than any of the other dredges. Its hydrodynamic drag component is however almost as high as that of the toothed mud dredge.

The low hydrodynamic drag of the Ket-ami and Scottish dredges reflect their low frontal area and absence of depressor plate devices.

DISCUSSION

The Bay dredge depressor plate approximates the criteria cited by Vaccaro & Blott (1987) for optimising the pressure drop behind a stalled horizontal wing in proximity with the ground. It is possible that this dredge is a hydrodynamic scallop catching device that has evolved over a period of time by trial and error.

The net downward force on the standard dredge is fairly high (greater than 2000N or 204kg) which should be more than adequate to maintain good bottom contact. Under normal operating conditions the net downward force will actually increase with speed and this should ensure better than necessary bottom contact.

At low speeds (up to 3 knots) the greatest source of drag on the toothed mud dredge is from friction and ploughing. At higher speeds (5–8 knots) the hydrodynamic component becomes dominant and is the component which will limit the towing speed. For the dredges using a cutter bar or mouthorgan bar (which does not protrude below

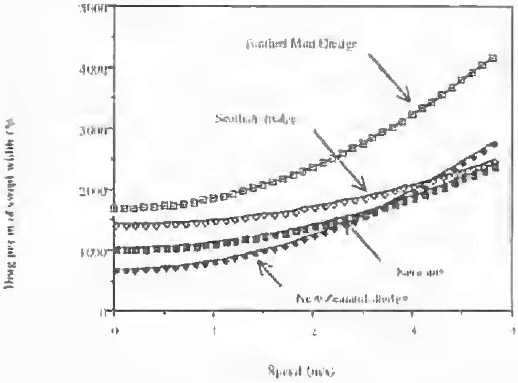

FIG.10. Comparison of dredge types with repect to their drag per m of swept width.

the skids) the friction and ploughing component of drag will be much reduced.

The box type dredges have a definite tendency to ride on the front or rear of the skids. This can be controlled by the warp length to depth and tow speed, or alleviated by the design modifications of skid extensions fore and aft. The tendency of the dredge to rock fore and aft may contribute advantageously or adversely to catching performance. It could be controlled to some extent by changes in warp length to depth, tow speed or the friction and ploughing forces (by altering tooth penetration). The addition of a rubber tyre and length of chain should help to reduce the tendency of the dredge to ride on its nose and could help to damp out fore and aft rocking.

Although the average downward contact pressure exerted by the toothed mud dredge is reasonably low, the point loading and dynamic action might mean that very high intermittent contact pressures will occur. The average downward contact pressure of the ring mesh bag and the other dredge types is very low and not likely to vary to any large degree.

The teeth and cutter bars of the toothed mud dredge, the tines of the Keta-ami and the sprung teeth of the Scottish dredge will exert a high point loading. Very high contact pressure is likely to contribute to damage of the catch and damage to the environment.

In terms of drag, the best performer was the New Zealand dredge. It had the lowest cost in terms of total drag at its operational speed of 3 knots. The toothed mud dredge performed poorly due to a much higher drag especially at 5–6 knots.

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